3ω power balance procedure on the NIF

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January 22, 2001

U.S. Department of Energy

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This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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January 22, 2001
NIF_0062073

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SUBJECT: 3ω power balance procedure on the NIF.

SUMMARY

This document defines the detailed NIF full system shot procedure to obtain 8% power balance as specified by the SDR002 3.2.1.04. Because the 48 quads of the NIF will be set up over a period of five years, obtaining power balance will naturally be accomplished in two steps. First, as each quad is brought online, the four laser beams within each quad will be tuned by setting the PABTS splitter ratios so that each beam will give the same laser power on target during low energy square pulse shots. During the quad activation period all of the technical tools and procedures will be developed that are needed for attaining full laser power balance. After the initial settings of the 48 PABTS, if no other tuning is done the overall NIF power balance is expected to be about <15%. In the second step, an iteration procedure with approximately 18 full laser system shots will be needed to obtain 8% power balance by tuning out the remaining systematic differences among the quads to an acceptable small difference of 2% rms (at 3ω). This rms difference is smaller than the expected variation of the injection energy or the amplifier gain, and is also of the same order as the laser energy diagnostic accuracy. Therefore, 8% power balance will require a number of precision measurements that will need accurate calibrations combined with a laser performance model that accounts and corrects for variations of the injection energy and the amplifier gain. This document is intended to specify the procedure and the flow-down of requirements from the system design requirement of 8% power balance. It is further intended to help guide the laser shot planning, the laser controls, and the laser performance operations model groups. It should provide input relevant to power balance tuning for the development of an operations model that includes post-shot analysis (as described in NIF_0046491), shot planning (as described in this memo), and pre-shot analysis.

1.   INTRODUCTION

Figure 1 summarizes the various tasks necessary to achieve 8% power balance. Before starting the set-up procedures, a number of calibration shots that can be performed within 4 eight hour shifts of NIF operations will be needed to ensure accurate laser power measurements and synchronization of the beams on each system shot. After the diagnostics

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are qualified, 10 laser shots will be required for each quad to set the PABTS splitter ratios to compensate for the systematic differences between the four beams in the quad. This will be accomplished by firing low energy, square output pulse shots and adjusting the splitters to equalize the 3ω outputs. This step will be performed once while activating a quad and might be repeated for the whole laser at other times, such as, at the start of important campaigns or when the tuning procedure to obtain 8% power balance is started. With only the initial PABTS splitter tuning, the projected systematic differences between quads will cause the power balance to be about <15% at this point. Several measurements and calculations will have to be developed during this initial quad setup to facilitate the later laser setup. After a number of quads have been set up and shots requiring power balance are scheduled, a shot campaign to tune out the systematic differences between quads to less than 2% will be done. This will require that the laser diagnostic data from the input sensor, the output sensor, and the FOA 3ω FOA diagnostic sensor be used together with the operations model to determine the systematic differences between the quads to the 2% level. It may require several iterations of low energy, square output pulse, 3ω shots to reach and confirm this accuracy. We estimate that six shots will be required during each iteration to average over the random variations in the ILS and in the amplifier gain and 3 iterations with six shots each will be required to reach the final settings. During the first iteration an initial set of measurements is taken and the laser settings are adjusted using the PAM wave plates to compensate for the differences between quads. The second set of six shots will indicate whether the laser settings have resulted in smaller systematic quad differences. The third iteration may be required to further reduce the systematic differences. On subsequent power balance campaigns, it is likely that only two iterations of six shots will be required.

This memo is structured as follows: In section 2 we will describe in detail the quad setup. In section 3 we summarize the 1ω and 3ω laser diagnostics and calibrations that need to be combined to obtain 3ω power curves (as described in detail in NIF_0046491). Section 4 summarizes the analytical (performed by R. Speck) and the numerical studies (performed by O. Jones) that define quantitatively which measurements and which accuracy will be needed to obtain and measure systematic differences to better than 2%. Section 5 summarizes action items that might result in improvements and shot savings.

2.   POWER BALANCE SET-UP SHOTS (15% pb)
In the period of 2004-2008 the 48 quads will be activated. To tune out the systematic differences among the 4 beams in each quad, 10 properly diagnosed full system shots will be required for each quad. We intend to perform these power balance setup shots with 10ns-long low-energy square pulses with 3ω power equivalent to that of the foot of a Haan-pulse. The desired pulse delivers an energy of 500J at 3ω on target which corresponds to approximately 3kJ energy at 1ω because of the low conversion efficiency at this low power. The reasons for this laser pulse choice are:
1) It is desirable to tune out difference among beams at the Haan-pulse foot level where power balance is most difficult to achieve for an indirect drive inertial confinement fusion campaign. At the peak of the Haan pulse, power balance will be improved because of laser saturation and the reduced sensitivity of the 3ω output to errors in the 1ω drive.

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2) A square pulse will allow us to use the 3ω calorimeters in the FOA 3ω diagnostic sensor to measure power differences between beams and quads. The 3ω calorimeters are more accurate than the 3ω power diagnostics.
3) Tuning out differences among beams and among quads with low energy square pulses instead of full power Haan-shaped pulses will allow us to perform these calibrations with minimal impact to the 3ω final optics. No laser glass damage is expected for $E_{3\omega}$ = 500J per beam.

One consequence of the high 1ω energy is the creation of significant amounts of shrapnel and debris. Disposable debris shields are desirable because there are no focal spot requirements for the tuning procedure. However, the requirements on the overall transmission and on the spatial uniformity are stringent:
1) The overall transmission must be known to an accuracy of about 0.5% before the shot.
2) The long-scale-length spatial non-uniformity can not exceed 10% without compromising the accuracy of the 3ω energy measurement.
Because it is not known at this time whether disposable debris shields will meet these requirements in 2004, a minimum debris target should be developed that will allow us to do the tuning shots with the standard debris shield (see 5.2).

Figure 2 shows a summary of the laser setup procedure for the initial setting of the splitter ratios for each quad. Before we fire the tuning shots, a number of shots for laser characterization and diagnostics calibrations will need to be performed. First, the conversion efficiencies to 3ω, the amplifier small signal gains, and the optical transmissions need to be characterized. A Laser Performance Operations Model (LPOM) will use this information to calculate the injection pulse out of the PAM into the main laser chain that will produce the desired low-energy square pulse on target. The calculated injection pulse will be confirmed with PAM shots before we propagate a pulse down the laser chain. In order to control PAM shot-to-shot variations with the low energy injected pulses, a following-pulse capability will need to be developed (see 5.1) to saturate the regenerative amplifier in the PAM so that the injection energy variations are tolerable (at the desired 3% level). Four full laser shots will be required to measure the 3ω laser energies with the 3ω calorimeters in the FOA 3ω diagnostic sensor to 2.4% accuracy (based on the 3ω energy measurement having a static error of 2.2% and a dynamic error of 1.6%). At this time, four well-characterized beam sampling gratings (BSGs) and proper debris shields are required for each quad being tuned. Targets to intercept the beams at TCC are also required. Using the results from these first four shots, the PABTS splitter ratios will be adjusted to compensate for the differences between beams and subsequently 4 more shots will be fired to verify that the splitter ratios have been set correctly. It might be possible to reduce the number of shots slightly by using a faster algorithm (see 5.3). At this point, no further tuning of the laser or pulse shape is required. Two more shots with high 1ω energy to measure saturated gain ratios of each beam for input into the LPOM will conclude the set up of the quad. After all quads have been set up this way, we expect that the 192 NIF beams will produce <15% power balance.

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3.   LASER DIAGNOSTICS AND CALIBRATION SHOTS

Accurate laser diagnostics is a prerequisite for power balance. In NIF_0046491 we have documented the strategy for accurate 3ω power measurements on the NIF, and in NIF_0058570, "Assessment of 3ω laser power and energy measurements on NIF" we have analyzed the diagnostics capabilities and defined the flow-down requirements to meet the needed accuracy. In this section, we briefly summarize the procedures and estimate the number of laser shots required for calibration of the 1ω and the 3ω diagnostics (see Figure 3).

The NIF beam diagnostics will receive full-aperture samples of the beam at the output of the SF4 spatial filter lens in the 1ω section and after leaving the target chamber focus lens in the 3ω section. The 1ω sample is the 0.1±0.05% reflection from a coated optic following SF4 that is sent to the output energy integrating diode and the output sensor where the near field and the pulse shape are recorded. The 3ω sample is the 0.5% first order diffraction off a grating (BSG) following the 3ω focus lens that is sent to detectors in the FOA where the energy and pulse shape are recorded. Both of these sampling optics will need to be accurately characterized to assure acceptable spatial beam uniformity of the sample beams and to allow corrections for errors that are introduced by any non-uniformity. Errors can also occur if target debris or laser damage change the transmission of the FOA optics or introduce non-uniformity in the beam. In order to minimize these errors a shot-to-shot update of estimates of the FOA transmission will be required. The laser damage inspection system and/or a near-field camera in the FOA 3ω diagnostic sensor might be used to determine the fractional area of the beam that is obscured by damage by the whole set of FOA optics. Furthermore, accurate measurements will require that the detectors are calibrated and flat fielded. These activities will be done first before the instruments are installed and later during the maintenance period between shots. Tasks that require dedicated NIF shots are the energy sensor calibrations against full aperture calorimeters and the verification of beam synchronization with Au disk shots with 100-200 ps laser pulses. This on-line synchronization check measures the Au x-ray emission produced by a short pulse laser shot. Two shots are probably required to obtain 30 ps accuracy but they might not have to be dedicated to the power balance effort. They can be shared with other NIF users who will require short-pulse shots for target diagnostics checks and development.

The metrology data from the 1ω sampling surface and the flat field calibration data will be used to extract the 1ω near field from the output sensor measurement. The near field information might be necessary to make corrections to increase the accuracy of the energy data from the 1ω and 3ω calorimeters as outlined in NIF_0046491 (cf. Fig. 3) and NIF_0058570. Present estimates show that the laser energy diagnostics will meet the requirement on accuracy and precision to allow power balance tuning, i.e. 2.8% rms accuracy for the 3ω energy diagnostic, 2.2% of which is static. In order to meet the 1ω requirements, system shots at roughly 1/3 of full 1ω energy into the roving calorimeters are necessary for on-line calibration of the 1ω output energy sensors. Only one bundle per laser bay can be calibrated at a time. A fast shot cycle is available that allows rapid sequential firing of the 12 bundles in each laser bay. The turn around between shots is limited by the cycle time for the calorimeters (estimated to be 30 to 40 minutes) so it should

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be possible to calibrate all 192 beams within 2 shifts of operations (equivalent to 2 NIF shots).

To supplement these calibration shots, measurements of the laser beam uniformity and 1ω and 3ω energies will be useful to test our modeling predictions, to establish trends in the FOA transmission, and to verify corrections to the energy/power measurement due to beam and sampling optics non-uniformity. These measurements will be performed on every system shot and for beams in laser bay 2 on shots into the precision diagnostic station (PDS). At present, we estimate that no dedicated shots allocated to the power balance campaign will be required for these tests resulting in a total shot count for calibrations of 14 shots (12 for 1ω calorimetry and 2 for verification of beam synchronization) in 4 shifts of NIF operations.

4.   POWER BALANCE CAMPAIGN (8% pb)

At the end of the activation of the 48 quads in 2008, full 8% power balance will almost immediately be required for the WBS2 symmetry campaigns. Full 8% power balance requires tuning out the systematic differences in laser performance among the various quads (see Fig. 4) to less than 2%. Random variations that will always be present during the low power tuning shots are expected to be large, approximately 9% rms, and present a significant challenge in matching the average performance of all quads to within 2% rms. Achieving this goal will require averaging over several full system shots and simultaneously correcting the 3ω output for the random variations in the main amplifier gain and in the injected energy. The 3ω output for each shot will be measured in the FOA 3ω calorimeter and the amplifier gain and injection energy will be determined from the 1ω input and output energy measurements. The 1ω measurements will provide input data for the Laser Performance Operations Model to estimate the corrections for the measured injection energies and amplifier gains on the shot. The latter step is essential to reduce the variation in the measured 3ω energy, $\delta E_{3\omega}$, to <2%. The correction also requires knowledge of the average PAM energy injected into each quad and the average amplifier gain for each bundle, i.e. these values averaged over several shots. These average values can be determined either during the tuning campaign shots or through the LPOM based on recent past system performance data. The total error in any correction will be the RSS sum of the error in the measurement (of injection energy or gain) on the shot and the uncertainty in the knowledge of its average value for each quad or bundle.

The 8% power balance tuning campaign will be performed like the power balance setup procedure with 10ns-long low-energy square pulses with power equivalent to that of the foot of a Haan-pulse. During this campaign, full laser diagnostics with 192 BSGs, suitable debris shields or a minimum debris target, and the calibrations of all energy sensors must be available. On each system shot in addition to the 3ω energy, the 1ω injection energy and the 1ω output energy will be measured. The accuracy and precision of these measurements is expected to be 2% and 1%, respectively. Eight measurements of the 1ω output energy will be made for each bundle, one for each beam. The input and output 1ω measurements will allow us to estimate the amplifier gain for each bundle on each shot. The design requirement for amplifier gain variation is 2% rms at 1ω corresponding to a contribution in

the variation of the 3ω energy of 4.8% rms. By averaging over two measurements of the injected energy (one for each quad) and eight measurements of the output energy (one for each beam) the bundle gain on a shot can be measured with a rms precision of less than 1%. By averaging over 6 shots the average gain of each bundle should be determined to within 0.8% rms. Taking the RSS sum of these two contributions, a measurement error of 1% and the uncertainty in our knowledge of the average bundle gain of 0.8%, yields an uncertainty in the corrected gain of less than 1.3% rms. Applying the factor of 2.4 to convert 1ω uncertainty at foot intensity to 3ω uncertainty gives a 3% rms contribution to the corrected overall 3ω shot-to-shot repeatability.

The input sensor energy measurement can be used directly to partially correct the 3ω output for variations in the injected energy for each quad. The specified injection energy variation is <3% rms which corresponds to a shot-to-shot random variation of 7.2% rms at 3ω. The short-term precision of the input sensor calorimeter is expected to be <1% rms. If we average over enough shots to obtain 0.5% rms uncertainty in our knowledge of the average injection energy (~36 high-repetition PAM shots), take the RSS sum as above, and apply the 1ω to 3ω multiplier, the injection energy contribution to the corrected overall 3ω shot-to-shot repeatability becomes 2.7% rms.

There are two additional sources of error that must be taken into account. These are the random variations in setting and maintaining the phase matching angle of the frequency doubling crystal in the FOA and the error in measuring the 3ω energy. The frequency conversion errors are estimated to contribute 1% to the random energy variations (Paul Wegner, *private communication*, 2000). Unlike the 1ω energy measurements where we were interested only in the repeatability, we must consider the total error (2.8% total, 2.2% static or systematic and 1.6% dyanmic or random) for the 3ω measurement. This is true because we are trying to balance the energies at the target, not make a correction that depends largely on repeatability. We make four measurements of the output of each quad, one for each beam. The estimated error in each of these measurements is 2.8%. If we assume that the errors are randomly distributed the error in the measurement of the quad energy is 1.4%.

Taking the RSS sum of the contributions to the variations in the 3ω energy which include: (1) the corrected injection energies (2.7%), (2) the corrected amplifier gains (3.0%), (3) the random tuning errors of the KDP (1%), and the errors in the energy measurements (1.4%) results in a total energy uncertainty of 4.4% for a single shot. Therefore, averaging over six shots should reduce the energy uncertainty to 2% (Ralph Speck, *private communication*, 2000). This 2% uncertainty was recently verified by detailed laser modeling (Oggie Jones, *private communication*, 2000). After the systematic differences are measured during the first set of six shots, we will reduce those by adjusting the PAM wave plates. During the initial set up probably 2 more iterations will be required, resulting in 18 shots for the 8% power balance tuning procedure. On subsequent campaigns, by taking advantage of data collected in previous campaigns, this number might be reduced to 12 shots. Without properly calibrated and fully functioning laser diagnostics and an up-to-date operations model the shot number will be unacceptably high. This can be understood by simply combining the variations of the 3ω energy due to variations in the injection energy, amplifier

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gains, KDP settings, and the energy diagnostics. Without corrections, the total variation would be 8.8%, requiring 16 shots for each iteration in order to reach 2% uncertainty in the quad performance.

Figure 5 summarizes the schedule for the 15% power balance setup procedure and the 8% power balance tuning campaign linking it to the current NIF schedule.

5.　ACTION ITEMS

1) A technique that allows saturated PAM operations for a low energy square pulse needs to be developed.
2) A minimum debris target needs to be developed for power balance shots applying hydrodynamic simulations. This effort might result into two different targets because of the different laser energies used during setup and full NIF 8% power balance tuning. The requirements on such a minimum debris target are:
   a) The target must not create amounts of shrapnel and debris that will affect the transmission of the debris shield by more than 0.5% over 10 shots with a total energy on target of 2kJ at 3ω and 12 kJ at 1ω per shot.
   b) The target must not scatter more than 10% of incident laser light to assure that the 3ω calorimeter readings are not affected by scattered radiation
3) During laser setup, 4 shots are required to measure the 3ω laser energies to 2% accuracy. In the next step, the PABTS splitter ratios will be tuned and subsequently 4 more shots are required to verify that the splitter ratios have been set correctly. A similar averaging procedure is also required for full power balance tuning. It might be possible to save one or more shots during each cycle by using a faster algorithm that allows tuning after 3 shots have been fired. The possible development of a faster algorithm needs to be investigated.
4) The present procedure determines the systematic differences for the foot of a Haan pulse. If the laser pulse shape is considerably modified a new tuning iteration will be required. The possibility of tuning the laser beams for a broad range of laser pulse shapes should be investigated.
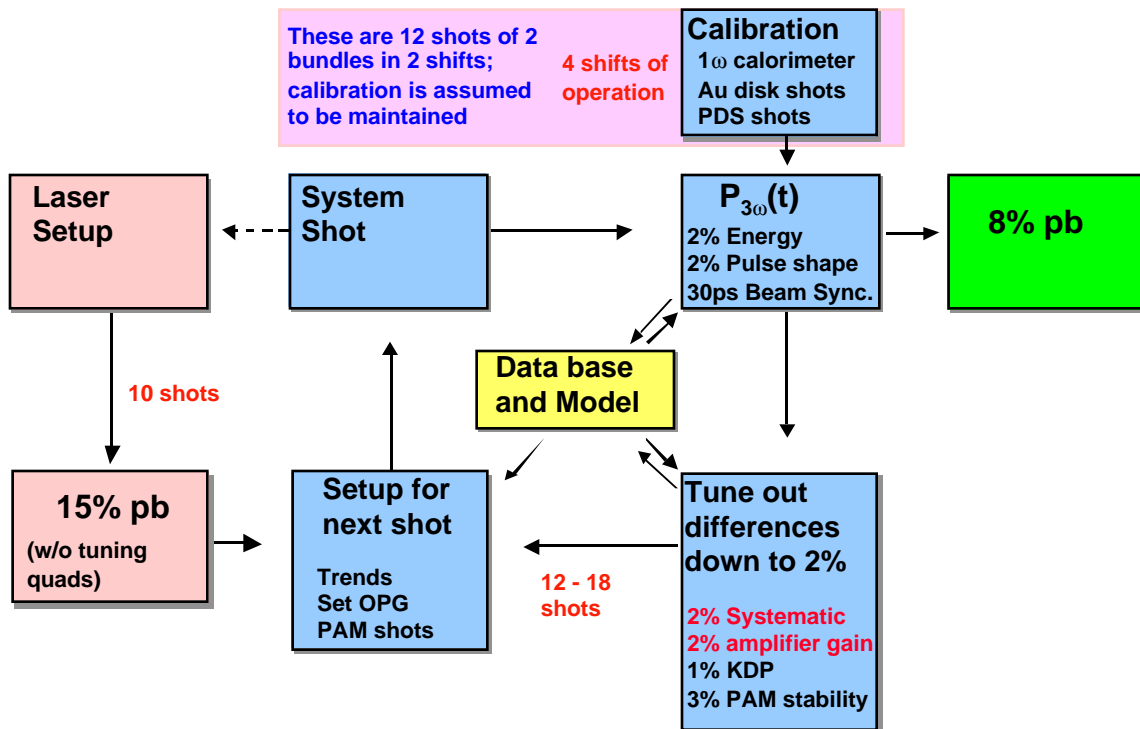
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FIGURES

These are 12 shots of 2 bundles in 2 shifts; calibration is assumed to be maintained

4 shifts of operation

Calibration
1ω calorimeter
Au disk shots
PDS shots

Laser Setup

System Shot

$P_{3\omega}(t)$
2% Energy
2% Pulse shape
30ps Beam Sync.

8% pb

10 shots

Data base and Model

15% pb
(w/o tuning quads)

Setup for next shot
Trends
Set OPG
PAM shots

12 - 18 shots

Tune out differences down to 2%

2% Systematic
2% amplifier gain
1% KDP
3% PAM stability

Figure 1. Summary of power balance set up, iteration, and calibration shots. Achieving power balance (pb) will require a total of 28 full system shots; 12-18 shots are dedicated to tuning.
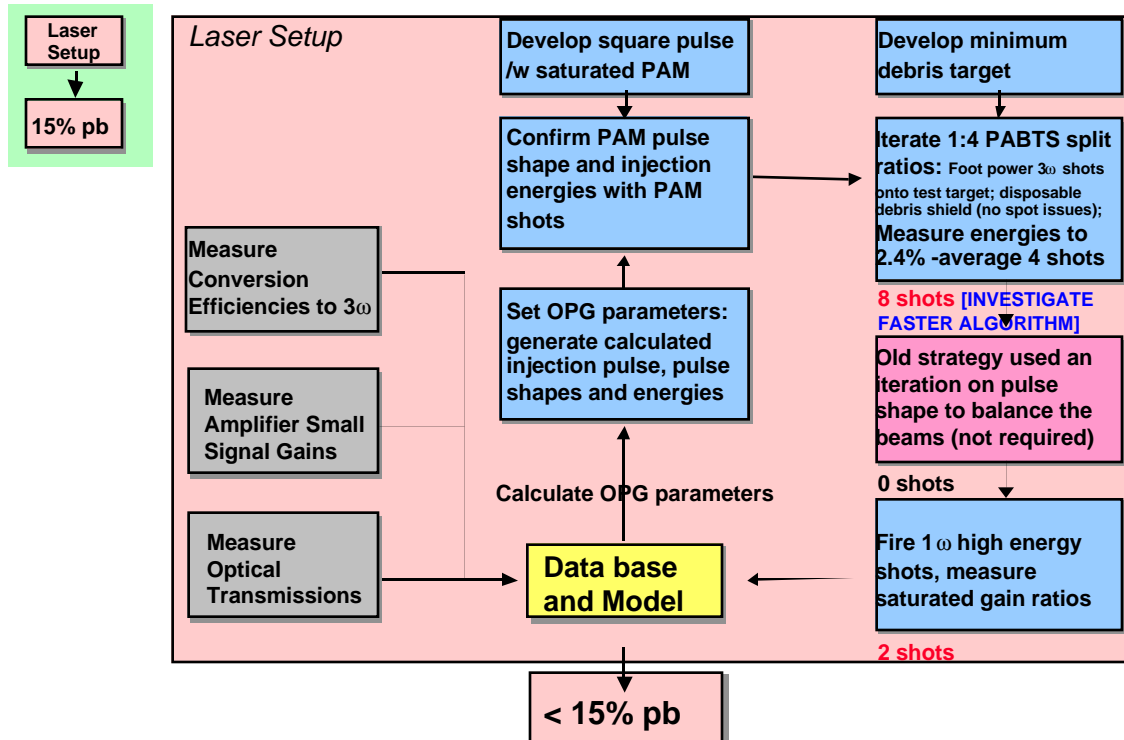
Figure 2. Schematic of the initial power balance procedure during laser setup requiring 10 shots per quad - includes 2 shots for model verification.
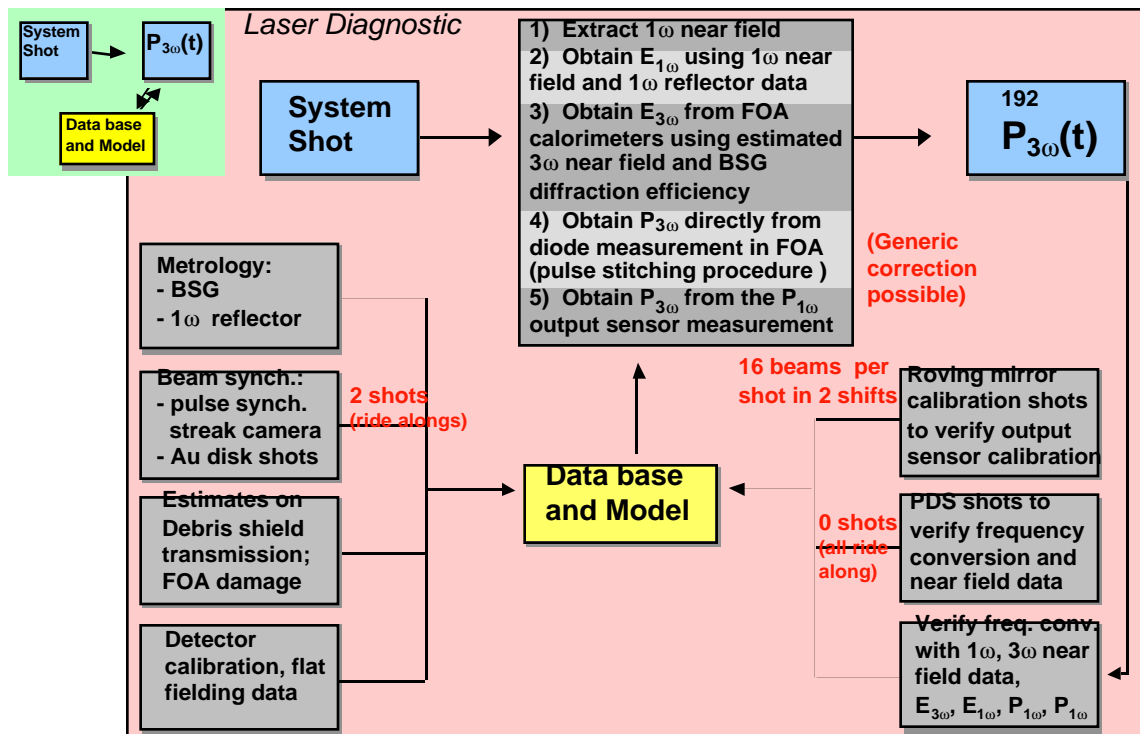

Figure 3. To obtain 1ω and 3ω energy and power requires off-line metrology and on-line performance checks using 4 full system shots.
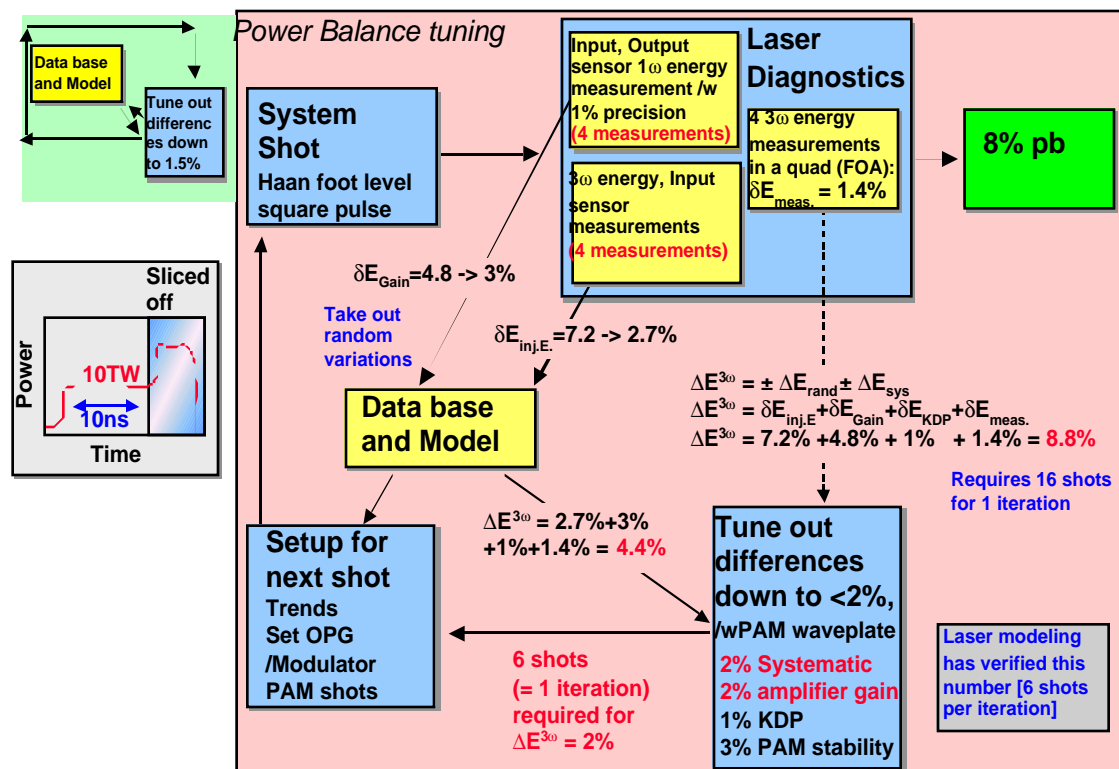
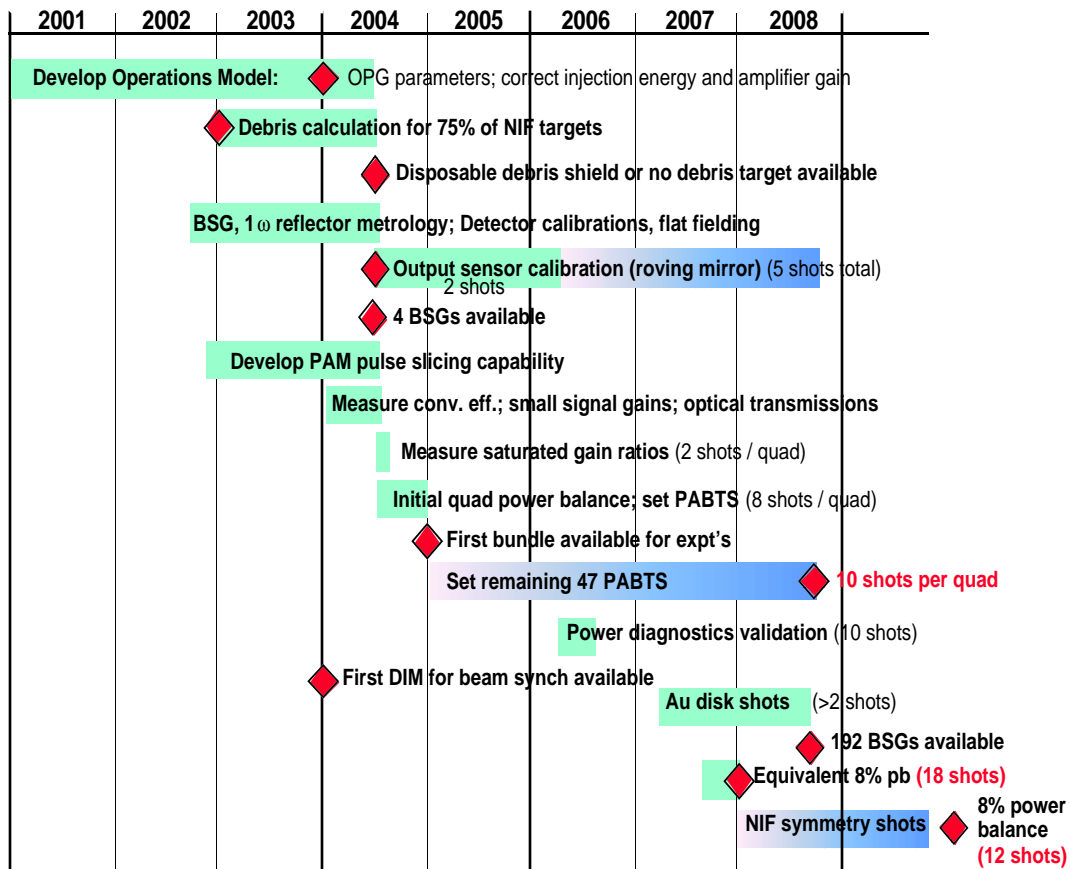Figure 4. Tuning out differences among quads will require 12-18 full system shots (for 2-3 iterations). A Haan foot power square pulse will be used with 500J (3ω), 3kJ (1ω), 10ns.

Figure 5. Power balance schedule.